# A liquid xenon PET camera - Simulation and position sensitive PMT tests

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S.Jan, J.Collot, E Tournefier
Institut des Sciences Nucléaires (ISN), 53 Avenue des Martyrs, 38026 Grenoble CEDEX, France

*Abstract*

A detector which uses liquid xenon in the scintillation mode, is studied for Positron Emission Tomography.
A simulation which only takes into account the basic physical processes, shows that the intrinsic transaxial resolution one can reach is $R_{minFWHM} = 1.5$ mm. Results on the performance of a position sensitive PMT operating in the UV range (180 nm) are presented.

## I. Introduction

This project aims at developping a Positron Emission Tomograph (PET) based on the use of liquid xenon (LXe) as an active medium. This PET will be dedicated to humain brain research, with a high spatial and timing resolution. Its application for an online ($^{11}C$) PET camera dedicated to hadrontherapy is also considered.
This development is proposed by three laboratories of the University of Grenoble and one industrial partner, Air Liquide, for the cryogenic system.
For this camera, we only want to use the scintillation detection mode of liquid xenon. The scintillation time decay of LXe (3 ns) could result in a significant progress in time resolution and in the sensitivity of the detector. This camera aims at obtaining a high image resolution ($\simeq$ 3 mm on image) and an increase of a factor 5 of the counting rate.
The execution of this project is organized along two phases : in the first place, the development of a full PET simulation (GEANT 4 - ROOT - IDL) and a R&D investigation which includes the construction of a small prototype to confirm the project feasibility, followed by the development and the construction of a full device.
We will present the operation principles of this device, its preliminary simulated performance and the first results obtained during the ongoing R&D phase.

## II. Why use liquid xenon ?

An important aspect of this project is the fact that we only want to use the LXe scintillation properties [2] and not its charge collection mode [3]. We can justify this by the following arguments :

- the scintillation efficiency of LXe is two times higher than the one of NaI which is the most efficient inorganic crystal
- its scintillation time decay (3 ns) is at least ten times faster than the best value of all the crystals considered in PET development (LSO, 40 ns)
- the scintillation yield as compared to the chargecollection efficiency of LXe is much less sensitive to the pollution of the liquid (few ppm)
- the drift velocity of free electrons charge (in collection mode) is too slow
- the use of a liquid active medium may enable us to devise novel detector geometries which could result in a sizeable amelioration of the camera performance

| Property | LXe | LSO |
|---|---|---|
| $\tau$ (fast) | 3 (98%) | 40 |
| $\tau$ (slow) | 25 (2%) | |
| Photons/MeV | 7.8 $10^4$ | 3.2 $10^4$ |
| Wave length (nm) | 178 | 420 |

Table 1
Comparison between LSO and liquid xenon as an active medium.

## III. Expected performance

In comparison with the tomographs which are commercially available today, the improvement we could reach in our project is given by the next points [4]:

- a factor 1.5 for the spatial resolution $\rightarrow$ Axial and transaxial resolution $\simeq$ 3 mm on reconstructed image (with $^{18}F$)
- a factor 5 for the counting rate
- a time coincidence window $\leq 5$ ns : reduction of random coincidences
- a good energy resolution to discriminate the scattered photons and to filter the ”compton noise”

## IV. Monte-Carlo simulation

The different steps which are performed in our simulation are the following :

- definition of a geometry for the liquid xenon (volume : 30 l max.) - GEANT 4 [5]
- definition of the cryostat - GEANT 4
- event generation in a water standard phantom - GEANT 4
- tracking of the $\beta^+$ which annihilates into two photons in water - GEANT 4
- tracking of the annihilation gammas - GEANT 4
- performance analysis of the detector - ROOT

- construction and analysis of sinograms - ROOT
- reconstruction with Filtered Backprojection method - IDL

## A. Phantom and event generation

A standard phantom for simulating the conditions prevailing during a brain study is a hollow cylinder 20 cm in length and diameter made of a thin plexiglass vessel and filled with water. The phantom is placed at the center of the field-of-view (FOV) in the scanner [6]. The $^{18}F$ $\beta^+$ energy is sampled with the Von Neuman algorithm in our Monte-Carlo program (*Fig. 1.*) [7].

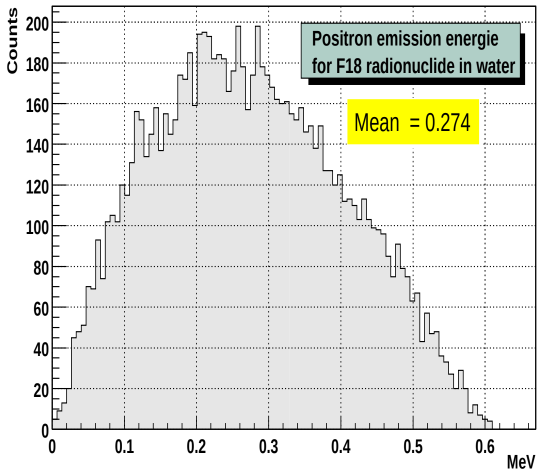


Figure 1: Kinetic energy distribution of the $\beta^+$ from the $^{18}F$ spectrum

One important physical effect which limits the PET spatial resolution is the $\beta^+$ range, or more exactly, the $\beta^+$ distance of flight in the human tissue. Here can see that the mean distance of flight before annihilation is 0.5 mm(*Fig. 2.*).

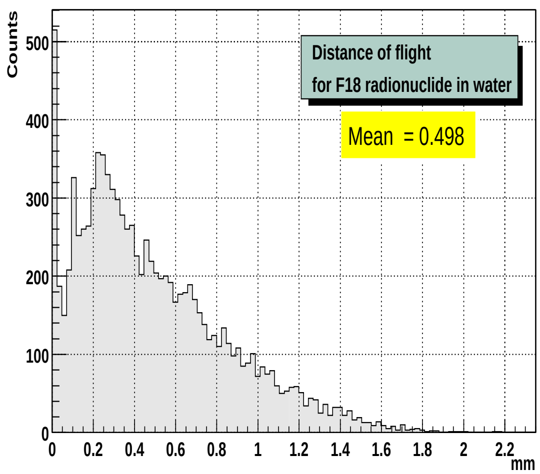


Figure 2: Distribution of the $\beta^+$ distance of flight in water from the $^{18}F$ spectrum

## B. Geometry of the liquid xenon volume

The liquid xenon is contained in a 5 cm thick ring of 30 cm of internal radius which covers 20 cm in the axial FOV. The total volume of LXe is 20.5 l.

| F.O.V. | 20 cm |
|---|---|
| $R_{min}LXe$ | 30 cm |
| $R_{max}LXe$ | 35 cm |
| Volume LXe | 20.5 l |

Table 2
Main dimensions of the simulated detection ring.

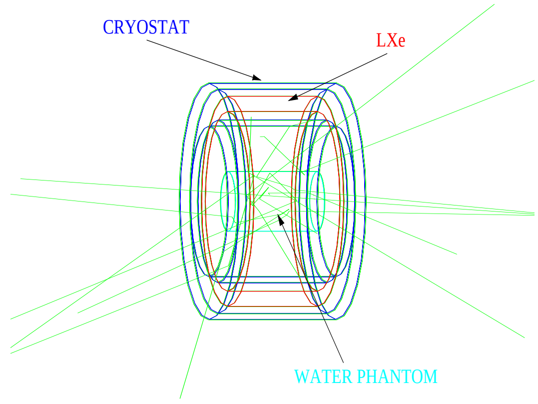


Figure 3: GEANT 4 geometry of the LXe tomograph. 10 $\beta^+$ were simulated in the water phantom for this picture. The tracks in green are photons.

## C. First results

### 1) Energy spectrum

We simulated the energy deposited by the two $\gamma$ in the liquid xenon. 200000 $\beta^+$ were generated in the water phantom.

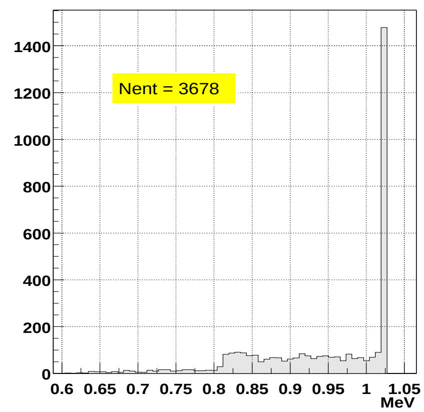


Figure 4: Energy deposit spectrum for real coicidences with a treshold of 300 keV per $\gamma$

The energy deposit spectrum for real coincidences with a treshold at 300 keV for each $\gamma$, give us the upper sensitivity ($S_{max}$) limit of the tomograph : $S_{max} = 1.8\%$

*2) Transaxial resolution*

We only simulated the contribution of the physical effects to the spatial resolution of the detector. 3000000 $\beta^+$ from the $^{18}F$ spectrum were generated at the center of the phantom (0,0,0). The energy threshold, per photon, was 300 keV. The acquisition is in the 2D mode, and we analysed a sinogram of real coincidences.

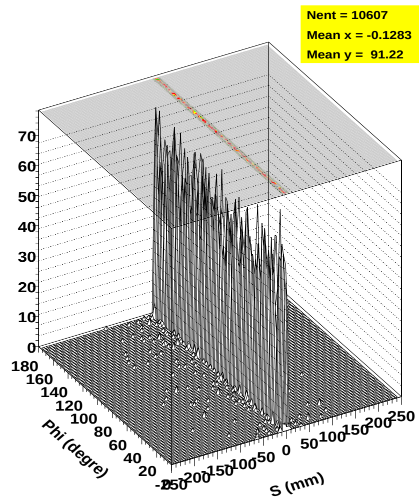


Figure 5: Simulated sinogram of the $^{18}F$ point like source

The non-co-linearity of the 2 $\gamma$ was not taken into account in this simulation. The contribution of this effect , at FWHM, is $r_1 = 1.3$ mm for our geometry.
At FWHM, the contribution of the $\beta^+$ distance of flight and the compton scattering in the LXe, for a threshold of 300 keV per $\gamma$, is $r_2 = 0.7$ mm (*Fig. 6.*).

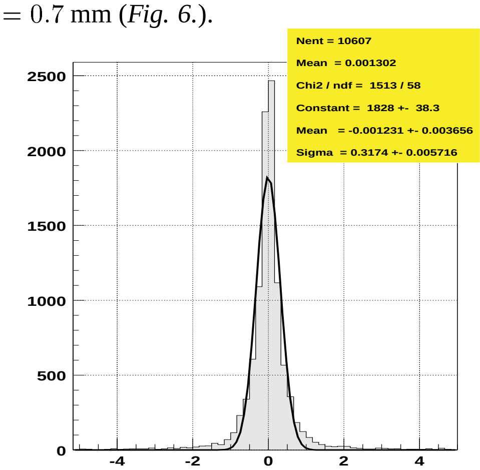


Figure 6: Center section of transaxial profiles

The evaluation of the optimal intrinsic transaxial resolution (only the physical contributions) at FWHM is :

$$R_{minFWHM} = r_1 \oplus r_2$$

$$R_{minFWHM} = 1.5 \text{ mm}$$

# V. R&D PHASE

## A. Test of a Hamamatsu PM

A position sensitive photomultiplier tube (HAMAMATSU R5900-00-C12) was tested. It is equipped with a quartz window and a RbCs photocathode. Its anode is composed of two planes of crossed plates which enable us to detect with a very good resolution the x and y barycentres of the light pulses.

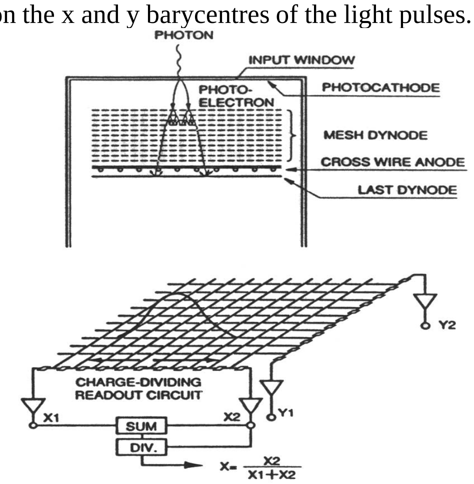


Figure 7: Description of position sensitive photomultiplier tubes using grid dynodes combined with a crossed plate anode.

The output signals from the crossed plates anodes are amplified and undergo Analog-to-Digital Conversion. Then these signals are read out by a computer for digital processing to locate the center of gravity mesure.

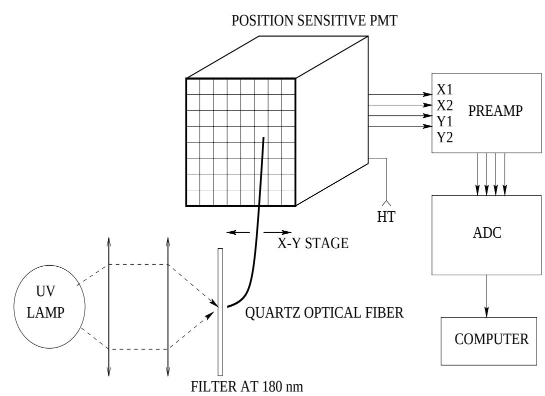


Figure 8: Schematic block diagram for position detection set-up.

The aim of these tests is to mesure the intrinsic spatial resolution of this PMT at $\lambda = 180$ nm. The results presented in this paper are mesured at room temperature.

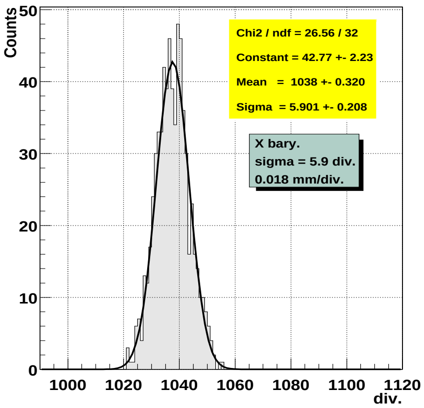


Figure 9: Spatial resolution at $\lambda = 180$ nm.

The resolution at FWHM :

$$R_{\lambda=180}\text{nm} = 0.25 \text{ mm}$$

### B. *Cryogenic system*

The liquid xenon cryogenic system is being built by Air Liquide. It will be ready in a few weeks. We expect some first results with this system before the end of this year. It will allow us to liquify and monitor in temperature up to 5 l of LXe.

## VI. Conclusions and perspectives

The preliminary results of a full simulation helped us to determine the intrinsic performance of this camera . For a point like source at the center of the tomograph, we could show that the intrinsic minimal resolution is $1.5$ mm.
The next step in the simulation will be to study and optimize the instrumental response of the camera so as to limit as much as possible the degradation of its intrinsic space resolution. It includes the simulation of the light collection in optical guides (Al tubes, quartz tubes...).
As a first result of our R&D activities, we may conclude that the position sensitive PMT Hamamatsu R5900, is a good candidate for the light detection at $\lambda = 180$ nm. This has to be confirmed at the temperature of liquid xenon (165 K). At the same time, we envisage to test Si photodiodes equipped with quartz windows.
As the test cryostat and the liquid xenon station will be operational at the laboratory in a few weeks, we foresee to built and test a small prototype cell (2.5 x 2.5 x 5 cm$^3$) by the beginning of next year, so as to confirm the instrumental performance obtained by simulation.

## VII. References

[1] S. Nagai, M. Watanabe, H Shimoi, H. Liu and Y. Yoshizawa, ”A new compact Position-Sensitive PMT for scintillation Detectors, IEEE Transactions on nuclear Science, Vol.46, NO. 3, JUNE 1999

[2] F. Favata, A. Smith, M. Davdaz, T.Z. Kowalski, Nucl. Instr. and Meth. **A297** (1990) 595-601

[3] V.Yu. Chepel,M.I. Lopes, A. Kuchenkov, R. Ferreira Marques, A.J.P.L. Policarpo, ”Performance study of liquid xenon detector for PET”, Nucl. Instr. and Meth. **A392** (1997) 427-432

[4] B. Bendriem, ”les détecteurs de positons : caméra PET - Caméra PET-SPECT”, revue de l’ACOMEN, 1998, vol.4, n°1, p. 34

[5] GEANT-detector description and simulation tool, Copyright CERN, Genève (1995)

[6] D.W. Townsend, M. Defrise, ”Image Reconstruction Methods in Positron Tomography”, CERN 93-02

[7] F. Emert, J. Missimer, K.L. Leenders, ”Monte Carlo Simulation of PET Scanners : Validation and Benchmarks”, MAY 1999